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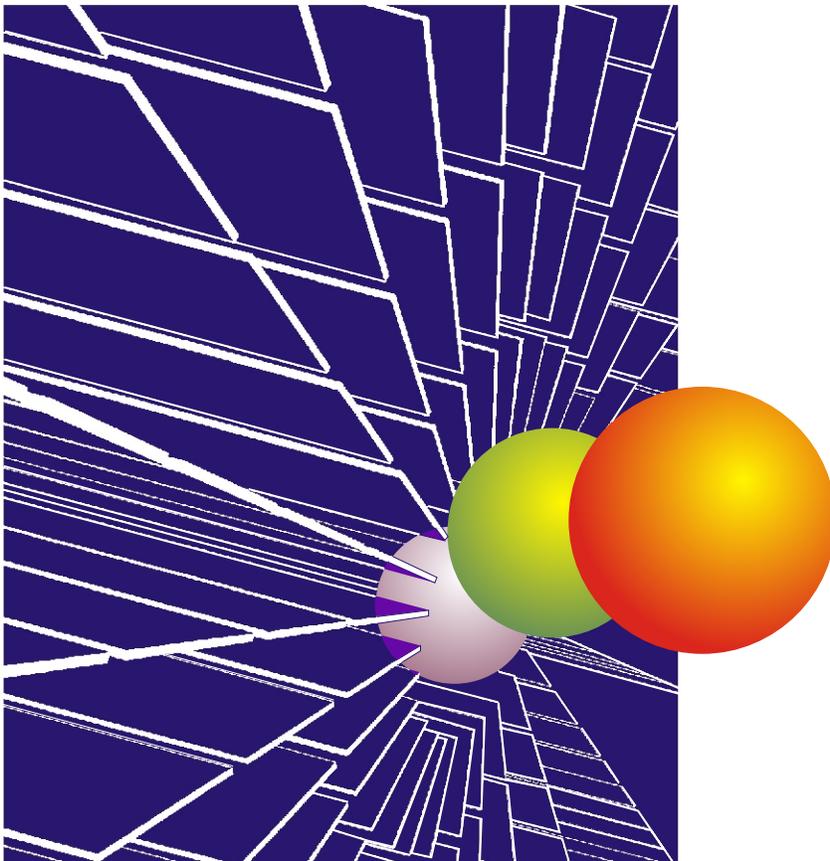
Research, Development and Technology

University of Missouri-Rolla

RDT 03-007

Rumble Strips in Missouri

RI 01-057



July, 2003

RESEARCH INVESTIGATION 01-057

SHOULDER RUMBLE STRIPS IN MISSOURI

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ROLLA, MISSOURI
DATE SUBMITTED: FEBRUARY 14, 2003

The opinions, findings, and conclusions expressed in this publication are those of the principal investigator and the Research, Development and Technology Division of the Missouri Department of Transportation.

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Technical Report Documentation Page

1. Report No. RDT 03-007	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle SHOULDER RUMBLE STRIPS IN MISSOURI	5. Report Date February 14, 2003		6. Performing Organization Code
	7. Author(s) Gary S. Spring, PhD, PE		8. Performing Organization Report No. RDT 03-007
9. Performing Organization Name and Address University of Missouri-Rolla Department of Civil Engineering Rolla, MO 65409-0030		10. Work Unit No. (TRAIS)	
12. Sponsoring Agency Name and Address Missouri Department of Transportation Research, Development and Technology P.O. Box 270-Jefferson City, MO 65102		11. Contract or Grant No.	
		13. Type of Report and Period Covered Final Report February 8 to November 30, 2002	
15. Supplementary Notes		14. Sponsoring Agency Code	
<p>16. Abstract The objective of this multi-phase project was to develop a set of guidelines for the use and design of rumble strips in Missouri which addresses the needs of both motorists and bicyclists and to specifically answer the two design questions posed. With regard to these questions, it was found that SRS narrower than the current width and that would fit within the construction joint area could indeed be designed and used safely. Key recommendations pertaining to SRS use are as follows:</p> <ol style="list-style-type: none"> 1. Install on all rural freeways and expressways. 2. Do not install in urban areas unless an engineering study has been conducted and has found that run off road crash history exceeds acceptable values and it is determined that SRS would be effective in reducing those numbers. 3. Speed limit must exceed 45 mph 4. On non-freeway/expressway sections, free shoulder width must exceed four feet (five feet in guard rail sections). Shoulders not meeting these criteria are not wide enough to accommodate both SRS and cyclists. In this latter event, decision must be made whether, for shoulders wider than two feet, whether crash history or cyclist usage should be given priority on the facility. When SRS are installed in this case, cyclists must be denied access to the facility. For shoulders less than two feet wide, SRS should not be installed. 5. The uninterrupted length of highway must exceed 1/30 of the design speed. <p>The following SRS design recommendations are proposed:</p> <ol style="list-style-type: none"> 1. Milled-in SRS with 5 inch grooves, 7/16 inches deep, on 12 inch spacing. 2. For all freeways use continuous strips that are 16 inches wide and 6 inches offset from the shy line 3. For non-freeways with shoulder widths exceeding 6 feet, use intermittent strips (12 foot gaps with 60 foot cycles) that are 16 inches wide and 6 inches offset from the shy line 4. For non-freeways with shoulder widths from 5 feet to 6 feet, use intermittent strips (same pattern as above) that are 12 inches wide, on the shy line 5. For non-freeways with shoulder widths from 2 feet to 5 feet, conduct needs studies based upon crash histories and bicycle use 6. For non-freeways with shoulder widths less than 2 feet, do not install SRS. <p>A process for evaluating the on-site performance of rumble strips to be used to refine the guidelines to best suit Missouri's conditions is also provided.</p>			
17. Key Word safety, rumble strips, highways		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price N/A

ACKNOWLEDGEMENTS

The author would like to thank Ms. Patricia Perez for her outstanding work in compiling information for this report and in writing the project interim report. Ms. Dinnu Joseph and Mr. Sudeep Deshmukh also deserve thanks for their work in the later stages of the project in pulling together information for the SRS guidelines. Finally, thanks to Mr. Don Davidson and Mr. David Silvester for their unflagging support throughout the project.

EXECUTIVE SUMMARY

The Missouri Department of Transportation (MODOT) began using shoulder rumble strips (SRS) on bituminous shoulders of interstate and freeway projects in 1991. Designs for concrete shoulders have since been added. Though successful in reducing run-off-the-road (ROR) accidents, shoulder rumble strips often encroach on the portion of shoulder used by bicyclists. In Missouri, many bicyclists ride in the two foot strip between the edge line and the rumble strip instead of on the right side of the rumble strip. They are reluctant to ride on the right side of the strip due to debris that is not swept clear by traffic wind currents. MODOT, consequently, posed two specific design questions to be addressed by this project. The first is whether strips could be narrowed from the current 36" width and be moved closer to the edge line to encourage bicyclists to ride on the right side of the strip further from traffic. The second question relates to problems associated with concrete pavements and follows from the first question. Currently concrete pavements are striped at 12' and their construction joint with shoulder is at 14'. Can SRS be designed narrow enough and be placed close enough to the striping so as to avoid the joint?

The objective of this multi-phase project was to develop a set of guidelines for the use and design of rumble strips in Missouri which addresses the needs of both motorists and bicyclists and to specifically answer the two design questions posed. With regard to these questions, it was found that SRS narrower than the current width and that would fit within the construction joint area could indeed be designed and used safely.

This Report provides a set of guidelines for the use and design of SRS in the State of Missouri. Key recommendations pertaining to SRS use are as follows:

1. Install on all rural freeways and expressways.
2. Do not install in urban areas unless an engineering study has been conducted and has found that run off road crash history exceeds acceptable values and it is determined that SRS would be effective in reducing those numbers.
3. Speed limit must exceed 45 mph
4. On non-freeway/expressway sections, free shoulder width must exceed four feet (five feet in guard rail sections). Shoulders not meeting these criteria are not wide enough to accommodate both SRS and cyclists. In this latter event, decision must be made whether, for shoulders wider than two feet, whether crash history or cyclist usage should be given priority on the facility. When SRS are installed in this case, cyclists must be denied access to the facility. For shoulders less than two feet wide, SRS should not be installed.
5. The uninterrupted length of highway must exceed 1/30 of the design speed.

The following SRS design recommendations are proposed:

1. Milled-in SRS with 5 inch grooves, 7/16 inches deep, on 12 inch spacing.
2. For all freeways use continuous strips that are 16 inches wide and 6 inches offset from the shy line
3. For non-freeways with shoulder widths exceeding 6 feet, use intermittent strips (12 foot gaps with 60 foot cycles) that are 16 inches wide and 6 inches offset from the shy line
4. For non-freeways with shoulder widths from 5 feet to 6 feet, use intermittent strips (same pattern as above) that are 12 inches wide, on the shy line
5. For non-freeways with shoulder widths from 2 feet to 5 feet, conduct needs studies based upon crash histories and bicycle use
6. For non-freeways with shoulder widths less than 2 feet, do not install SRS.

A process for evaluating the on-site performance of rumble strips to be used to refine the guidelines to best suit Missouri's conditions is also provided.

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1.0 INTRODUCTION

Highway shoulder rumble strips (SRS) are intended to alert drivers of errant vehicles by providing audible and tactile warning. The Missouri Department of Transportation began using shoulder rumble strips on bituminous shoulders of interstate and freeway projects in 1991. Designs for concrete shoulders have since been added. Though successful in reducing run-off-the-road (ROR) accidents, shoulder rumble strips often encroach on the portion of shoulder used by bicyclists. Currently many bicyclists ride in the two foot strip between the edge line and the rumble strip instead of on the right side of the rumble strip. They are reluctant to ride on the right side of the strip due to debris that is not swept clear by traffic wind currents. The Missouri Department of Transportation posed two specific design questions to be addressed by this project. The first is whether strips could be narrowed from the current 36" width and be moved closer to the edge line to encourage bicyclists to ride on the right side of the strip further from traffic. The second question relates to problems associated with concrete pavements and follows from the first question. Currently concrete pavements are striped at 12' and their construction joint with shoulder is at 14'. If the strip is moved closer to the edge line as proposed in question 1, it would be desirable to have it narrow enough to avoid the joint.

2.0 RATIONALE AND SIGNIFICANCE

There exists a dichotomy between the needs of the motoring public and the needs of bicyclists. Motorists need as much warning as possible that they are encroaching on the shoulder which requires, SRS as wide, deep and near to the traveled way as possible. Bicyclists need adequate clear space on shoulders to ride safely and need to be able to cross rumble strips without incident which requires, SRS as narrow and shallow as possible. The key issue is that the SRS must produce adequate vibrational and auditory stimulation for motorists while providing adequate space for bicyclists to safely use the facility.

2.1 Objective

The objective of this multi-phase project was to develop a set of guidelines for the use and design of rumble strips in Missouri which addresses the needs of both motorists and bicyclists. The two design questions posed in Section 1.0 are answered in the following pages and a set of draft guidelines are described. Additionally, a process for evaluating the on-site performance of rumble strips to be used to refine the guidelines to best suit Missouri's conditions is presented.

2.2 Discussion of Present Conditions

As stated above, MODOT currently uses 36" widths for its rumble strips which are placed 24" from the painted edge line. This causes significant safety problems for bicyclists in the traveled way. This research addresses this problem.

3.0 TECHNICAL APPROACH

The work for this project was completed in three phases as described below.

Phase I

A literature review of current design practices was conducted. A summary of the review's findings were used to generate a list of alternative rumble strip designs and locales who are the most active in the use of SRS. The summary was submitted in an interim report to MODOT in May 2002.

Phase II

A summary of state practices for SRS use and design across the United States was compiled and was used to develop SRS design guidelines for Missouri. See Section 4.0.

Phase III

A set of design guidelines which include information on where and when to use rumble strips, alternative designs and evaluating on-site performance were developed. See Sections 5.0 and 6.0.

4.0 RESULTS AND DISCUSSION

The following discussion explains the choices made for the draft SRS policy provided in the Appendix. The choices are:

1. Warrants
2. Type of SRS (milled, rolled, formed, raised)
3. Continuous versus intermittent
4. Pattern (A and B in Figure 4.1)
5. SRS transverse length (C in Figure 4.1)
6. SRS depth (E in Figure 4.2)
7. Offset from shy line (in Figure 4.1)

The last four items relate to dimensions which are depicted in Figures 4.1 and 4.2.

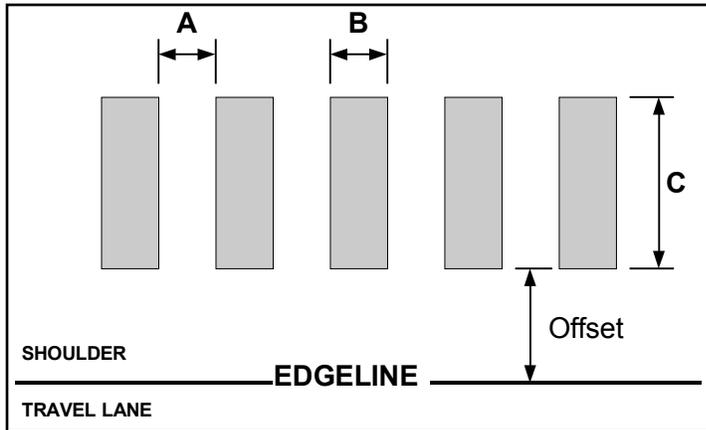


Figure 4.1. SRS Planar Dimensions (Isackson , 2000)

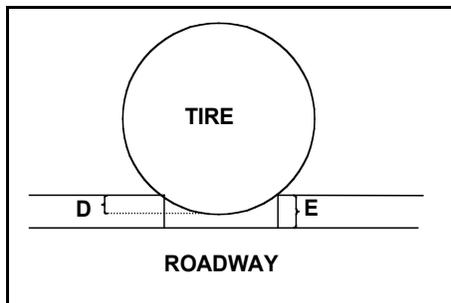


Figure 4.2. SRS Elevation Dimensions (Isackson, 2000)

4.1 Warrants

In a recent synthesis of SRS practice in the United States, Nedzesky (2001) notes that specific warrants for SRS installation do not exist. However, numerous States have guidelines, criteria, or recommendations regarding installation requirements of SRS. The fact is that SRS should not be installed where not necessary or appropriate. A blanket policy to install in all situations would not be cost effective nor would it meet the needs of the traveling public –motorists nor cyclists. Elefteriadou (2000) enumerates several problems associated with SRS (including cyclist concerns, maintenance issues and increases in ambient noise levels). It is for these reasons that a set of warrants was developed for these guidelines.

The following warrants are proposed:

1. Facility Type. Install on all rural freeways and expressways.

2. Urban versus Rural. Do not install in urban areas unless an engineering study has been conducted and has found that run off road crash history exceeds acceptable values (Ohio, for example, uses 25 crashes per hundred million vehicle miles) and it is determined that SRS would be effective in reducing those numbers.
3. Speed limit. Speed limit must exceed 45 mph
4. Free Shoulder Width. On non-freeway/expressway sections, free shoulder width (that available for cyclists) must exceed four feet (five feet in guard rail sections). Shoulders not meeting these criteria are not wide enough to accommodate both SRS and cyclists. In this latter event, decision must be made whether, for shoulders wider than two feet, whether crash history (Ohio for example as above) or cyclist usage (for example, one state uses volumes exceeding 25 ADT for the peak three months of the year) should be given priority on the facility. When SRS are installed in this case, cyclists must be denied access to the facility. For shoulders less than two feet wide, SRS should not be installed.
5. Uninterrupted Length. The uninterrupted length of highway must exceed 1/30 of the design speed.

4.1.1 Facility Type

SRS are designed to prevent run off road (ROR) crashes that are caused by driver error. That is, crashes where drivers were drowsy or inattentive which the National Highway Traffic Safety Administration (NHTSA) estimates to be a contributing factor in approximately 38% of run-off-road crashes (NHSTA, 2000). Applying these numbers to Missouri statistics this translates to about 7,800 crashes per year (MODOT, 2000). SRS are not designed for run off road crashes whose causes relate to loss of control due to poor geometry, for example. Drowsiness most often occurs in situations where the road geometry is straight, flat and monotonous – in short, on most freeways and expressways. Put another way, the types of ROR crashes for which SRS are designed are more likely to occur on freeways and expressways. Furthermore, this type of facility is high speed making it much more likely that, when a crash does occur, its severity will be high.

Additionally, FHWA (2001) recommends that continuous, milled shoulder rumble strips be installed on rural freeways and expressways on the National Highway System (NHS) as an effective means of reducing single vehicle, run-off-road crashes caused primarily by any form of motorist inattention. While they may be installed on a project-by-project basis, economies of scale and timely implementation of shoulder rumble strips make system-wide installation projects highly desirable.

4.1.2 Urban versus Rural

Urban areas by their nature typically do not allow for long, monotonous stretches of highway. They are also high density which makes SRS noise undesirable. Several state policies do not allow for installation of SRS in urban and residential areas. FHWA recommends that rumble strips should not normally be used in urban or suburban areas (FHWA, 2001).

4.1.3 Speed Limit

Numerous States have recommended a minimum speed limit of 50 mph on all roads in which SRS are to be installed (Nedzesky, 2001). Additionally, FHWA recommends rumble strips should not normally be used along roadways where prevailing speeds are less than 50 mph (FHWA, 2001). The warrant proposed for use in Missouri, 45 mph, derives from these recommendations and from the fact that very few run off road crashes occur at lower speeds thus making the installation of SRS unnecessary.

4.1.4 Free Shoulder Width

Fifty four percent of states surveyed by Minnesota DOT (Isackson, 2000), have some type of SRS restriction based upon shoulder width. Shoulders that are less than four feet wide do not have the minimum usable width recommended by AASHTO for bicycle travel (AASHTO, 1999). A bicyclist occupies approximately 30 inches laterally and requires approximately 40 inches to operate safely. Figure 4.3 depicts a bicyclist operating within the four foot shoulder mentioned above. The tape on the roadway simulates the fog line, twelve inches of rumble strip and five feet of clear shoulder due to the presence of guardrail.



Figure 4.3 Bicyclist Operating in Recommended Shoulder Geometry (Perez, 2002)

Table 4.1 reflects FHWA's recommendations in this regard. The recommendations in the proposed guidelines follow these recommendations.

Table 4.1 FHWA Shoulder Width Recommendations

Shoulder Width (mm)	Problem	Reasoning
0 – 609 (0 - 1.9 ft)	No	Shoulder too narrow for SRS or bicyclist.
610 – 1219 (2 – 3.94 ft)	Yes	Shoulder may be wide enough for SRS or bicyclist.
1220 – 1829 (4 – 5.9 ft)	Yes	Shoulder might be wide enough for both SRS and bicyclist.
1830 + (6 ft+)	No	Shoulder wide enough for SRS and bicyclist.

[Nedzesky, 2001]

If a minimum clear shoulder width does not exist lane widths may be reevaluated. If lanes are wider than 12 feet, their extra width may be used to increase shoulder width if such increase would address the SRS/bicyclist problem.

4.1.5 Uninterrupted Length

Oklahoma (2000) uses the criterion of uninterrupted length as a warrant for SRS installation. The reasoning is that SRS are designed to help drowsy or inattentive drivers stay on the road. One of the prime contributors to these phenomena is length and monotony of geometries uninterrupted by features requiring driver action. It is for this reason that it is proposed to adopt this same criterion as a warrant for SRS in Missouri. The minimum uninterrupted length equates to approximately two minutes of drive time. It is equal to one thirtieth of the road section's design speed in miles per hour. For example, on a 60 mph section of road this translates to a required uninterrupted length of two miles or two minutes of travel time.

4.2 Type of SRS

There are four types of shoulder rumble strips: milled, rolled, formed, and raised. They differ in installation procedure and shape. Of the four types, milled and rolled are the most prevalent in design.

- Milled rumble strips are formed by grinding the surface of either concrete or asphalt pavements.
- Rolled rumble strips are formed by pressing rounded or v-shaped bars into freshly paved asphalt shoulders with a special roller.
- Formed rumble strips are created by pressing forms with the desired rumble strip dimensions in freshly placed concrete.
- Raised rumble strips can be thought of as mini speed bumps, formed on top of the finished pavement surface.

The milled design was chosen as the preferred technique for the following reasons:

1. Raised rumble strips should not be used on Missouri roads due to the need to snow plow which destroys them. This design is appropriate for climates where snow removal is not an issue.
2. Formed rumble strips can only be used for new concrete pavements. Given there exists controversy regarding the use of formed strips (Chen (1994) showed that milled strips caused 7.2 times greater vibration and 60% louder sound than the formed-in strip on PC concrete yet a 2001 study by the FHWA indicates that formed rumble strips provide vibration and sound stimuli similar to milled), it is recommended that the contractor be allowed to choose this method of installation when constructing a new concrete pavement.
3. The rolled rumble strips have considerable maintenance and construction problems. For example, Moeur (2000) found that when installing rolled rumble strips the roller often does not track straight along the roadway edge line causing the rumble strip pattern to displace laterally across the shoulder, sometimes completely to the far edge of the shoulder. In a 1998 study, Perillo found that rolled rumble strips cause a reduction in shoulder asphalt density due to non-uniform compaction during construction. The increased voids, formed along the joint, trigger premature degradation of the shoulder. Additionally, the excess material resulting from the installation may increase maintenance problems after the pavement stabilizes, particularly when traversed by vehicles and snow plows. The rolling process often causes excess asphalt pavement to “push up” above the pavement surface, thus when plowed the excess pavement is scraped off reducing the effectiveness of the SRS. Also, the rolled rumble strips are typically inconsistent in depth due to many variables (for example, pavement temperature and asphalt density) during resurfacing that affect the rate of the hardening of the asphalt. Elefteriadou, et al, (2000) reported problems related to the installation of rolled rumble strips which include the aggregate being crushed by the ribs of the roller, shoving of the asphalt, and the pipes of the roller flattening with use. Both rolled and formed rumble strips can only be installed when the pavement is first placed. Thus, they cannot be used when rumble strips are identified as a countermeasure for road segments with high run-off-the-road accident rates. The milled-in approach is the only way to install rumble strips on an existing pavement. Finally, Wood (1994) found that contractors believe that the milled in grooves are more practical than rolled in.
4. Milled SRS produce significantly higher vibration and auditory stimuli than do rolled. Chen (1994) performed an analysis of milled, rolled and corrugated SRS in 1994 at 112 different locations on two Interstates in Virginia that showed that milled SRS produce 12.5 times more vibration stimulus and 3.35 times more auditory stimulus than rolled. Indeed, the study noted that an increasing number of jurisdictions believe that "rolled rumble strips have very little effect on trucks." Perillo (1998) found that after rolled rumble strips have become worn, they typically have long sections of smoothed out patterns that exhibit less noise and have little or no effect on fatigued drivers. Outcalt (2001) found that milled SRS produce the best vibration stimulus and recommended it for use. Perillo (1998) measured noise levels produced by rolled and milled rumble strips while a truck passed over the rumble strips. The sound level within the cab traveling at 65 km/h was 86 decibels for rolled rumble strips and 89 decibels for milled rumble strips. The 3-decibel difference is a

perceptible difference. Due to the increased noise and vibrations, milled rumble strips were deemed to be more effective

5. Milled SRS address biker concerns. Although the League of American Bicyclists indicated that rolled in rumbles are preferable to milled in designs (LAB, 2001) a 1999 study by Moeur found that while milled rumble strips were not considered enjoyable on which to operate a bicycle, they did not cause any significant vertical motion or instability of the bicycle. This is because bicycle wheels rode over the tops of the indentations without dropping completely into the grooves. The 2001 Outcalt study, mentioned earlier, was based in part upon the input of 29 bicyclists as well as vibration and auditory data collected in four different types of vehicles.
6. Milled SRS are more practical. Milled shoulder rumble strips usually require a smaller width of space on the shoulder than other types of strips (Harwood, 1993). The narrower width of the strip allows more shoulder room for the bicyclist to maneuver on the right side of the shoulder. Cheng (2000) pointed out that since milled SRS may be installed anytime, the shoulder can be used as a temporary travel lane without detours during construction.

Based upon the advantages offered by milled SRS, 70% of states in the US use milled SRS and FHWA recommends their use as well (FHWA, 2001; Nedzesky, 2001).

4.3 Pattern

The key considerations in the choice of SRS pattern are, once again, the levels of vibration and noise produced. Shoulder rumble strips are effective when they produce sound and vibration great enough to alert drifting drivers that they are leaving the travel lane. Vibration and noise magnitudes vary with design type and the dimensions of the strips.

The 5 inch width with 12 inch repeat is proposed for use in Missouri (referring to Figure 4.1, B = 5 inches and A = 7 inches) for the following reasons:

1. The Bachman study (2001) found that this pattern was not only the one preferred by bicyclists but also provided more than adequate noise and vibration levels for motor vehicles.
2. A large number of states use this pattern with success (Nedzeski, 2001; Chen, 1994)

Elefteriadou et al (2000) observed that the levels of vertical acceleration and pitch angular acceleration of the motor vehicle frame generated by the different rumble strips were insignificant and based his assessment of the effectiveness of different rumble strip patterns upon the results of noise level tests.

Khan and Bacchus (1995) have cited research indicating that a 4 dB(A)-level increase above ambient noise levels is adequate to be recognized as a warning device. Although this finding may be helpful, researchers have noted a lack of guidance with regard to what is the required sound level generated by shoulder rumble strips to alert a drowsy or sleeping driver (Bachman 2001; Torbic et al. 2001). In the absence of such information, Outcalt was helpful in describing human perception of changes in sound levels. Sound intensity is usually given in decibels, which is on a logarithmic scale from 0 (the threshold of hearing) to 160 (level at which perforation of the eardrum would occur). Table 4.2 shows the approximate human perception of changes in sound level (Outcalt, 2001). In a 1999 study, the League for the Hard of Hearing measured decibel levels for common transportation sounds as shown in Table 4.3.

Table 4.2. Approximate Human Perception of Changes in Sound Level

Change in Sound Level (dB)	Change in Apparent Loudness
1	Imperceptible
3	Barely noticeable
6	Clearly noticeable
10	About twice (or half) as loud
20	About four times(or one fourth) as loud

Table 4.3 Common Transportation Sounds and Their Associated Decibel Level

DB	Sound	dB	Sound
70	freeway traffic	90	Truck
85	heavy traffic	95 - 110	Motorcycle
85	city traffic inside car	110	car horn

source: League for the Hard of Hearing

Elefteriadiou et al. (2000) reported sound levels inside the passenger compartment of a minivan when traversing six different milled SRS at speeds of 72 and 88 kph (45 and 55 mph). While at the slower speed, the sound levels increased from an ambient level of 68 dB to approximately 79 dB. Likewise, at the higher speeds, the sound levels increased from an ambient level of 65 dB to approximately 81 dB.

Higgins and Barbel performed research in Illinois in 1984 regarding vibration and noise produced by SRS. While it was determined that outside noise did not significantly vary with different types and configurations of SRS, it was determined that SRS produced a low frequency noise that increased the ambient decibel (dB) level an additional 7 dB over noise levels produced by traffic on normal pavement. In general, most measured frequencies were between 50 and 160 Hertz (Hz). [Higgins and Barbel 1984]

In 2001, the Pennsylvania Department of Transportation (PENNDOT) published results of rumble strip configuration tests, which included bicyclist performance measures. Table 4.4 shows these test results. The Table shows how decibel level varies with depth and transverse width and bicycle satisfaction. All patterns are continuous with a 12-inch spacing between grooves and have “narrow” width. All patterns used groove lengths between 16-17 inches (406-432 mm). [Bachman, 2001]

Table 4.4 PENNDOT Rumble Strip Configurations Tested (Source: Bachman, 2001)

Test Pattern	Rumble Strip Dimensions, inches (mm)			Performance for Bicyclists		Vehicle Sound Difference db (A) (Rank)			
	Groove Width	Groove Spacing	Groove Depth	Composite Score	Rank	55 mph (88 km/h)	45 mph (72 km/h)		
1	7 (180)	5 (130)	0.5 (13)	0.97	#6	23.7	#1	11.6	#2
2	5 (130)	7 (180)	0.5 (13)	0.50	#3	18.5	#2	10.0	#4
3	5 (130)	7 (180)	0.375 (10)	0.12	#2	16.1	#3	6.8	#5
4	5 (130)	6 (150)	0.5 (13)	0.66	#5	16.0	#4	15.2	#1
5	5 (130)	6 (150)	0.375 (10)	0.50	#3	13.9	#5	10.9	#3
6	5 (130)	7 (180)	0.25 (6.3)	0.003	#1	13.0	#6	6.3	#6

Pattern 3 was recommended for higher-speed roads, near 55 mph (88 km/h). For lower-speed roads, near 45 mph (72 km/h), Pattern 5 was recommended. PENNDOT will install pilot rumble strips designed from Patterns 3 and 5 on non-freeway routes that have shoulders at least 6 feet wide. Offset was not discussed. [Bachman, 2001]

4.4 SRS Width

The choice of SRS width, unlike pattern and depth, has more to do with duration of vibration and noise than with their magnitude. The time that errant drivers spend on rumble strips is an important issue. Rumble time is extremely brief. For a vehicle leaving the road at a 3° angle and traveling at 50 mph, time of contact is only about 0.25 seconds. Larger departure angles, of course, result in even shorter contact times. It takes a lot of noise to wake drivers in such a short amount of time. We must be conservative in making modifications to this measure.

Elefteriadou et al (2000) concluded that rumble strips which produce 4 dB (A) increases or above will be readily detected by motorists who are awake if the noise level is sustained for 0.35 seconds or longer. If the noise increase is only 2 dB (A), the pulse length should be at least 0.90 seconds. The pattern described in the previous section provides increases of around 7 dB. Therefore, one may cautiously estimate that required duration could decrease commensurately.

Not enough research has been done in this regard to be definite about the efficacy of reducing the SRS width from the 16 inches commonly practiced across the country and the width recommended by FHWA (2001). However, there may exist compelling reasons to allow for 12 inch widths on shoulders that would compromise bicyclists' free space. Indeed, several states currently use a 12 inch minimum width and FHWA allows, in its recommendations, for this width when shoulder widths cannot accommodate the wider value. Thus, it is recommended that 16 inch SRS be installed, where warranted, on all shoulders that are at least six feet wide. For shoulders that are less than five feet wide, an engineering study must be performed, as indicated in section 4.1.4, Table 4.1 to determine if indeed a SRS may be installed.

4.5 SRS Depth

Once again, there exists a dichotomy between the preferences of bicyclists and the safety needs of motorists. In general, bicyclists would prefer the least amount of tire drop, and therefore shallower cuts. Unfortunately, this depth is directly related to the noise decibel level that a rumble strip produces. For motorists, the deeper the cut, the louder the noise. Isackson (2000) noted that the actual dimension of the SRS varies only slightly from State to State, namely, 1/2 inch deep.

A depth of 7/16 inches is recommended for use in these draft guidelines for the following reasons:

1. Recent studies have demonstrated that noise and auditory stimuli produced by 3/8 inches are adequate for motorists (Elefteriadiou et al., 2000; CalTrans, 2001; Outcalt, 2001). Thus, with a tolerance of 1/16 inches the recommended 7/16 inches assures a minimum depth of 3/8 inches.
2. FHWA (2001) advises that a 3/8 inch depth provides reasonable warning for motorists
3. The League of American Bicyclists (LAB) indicated that a bicycle tolerable rumble strip design would include a depth of 3/8 inches (LAB, 2001). Several studies have indicated that this depth is acceptable to bicyclists (Outcalt, 2001, Elefteriadiou et al., 2000; Bachman, 2001).

4.6 Continuous versus Intermittent SRS

SRS may be placed either continuously or with intermittent gaps. It is recommended that continuous SRS be used on all limited access highways where SRS are used and that intermittent SRS, with a pattern of 12 foot gaps and 60 foot cycles, be used elsewhere for the following reasons:

1. Continuous design has been shown to be more effective than intermittent design in lowering the number of serious accidents (Nedzesky, 2001).
2. Continuous SRS provide roadway delineation in conditions where the roadway edges would otherwise not be distinguishable. In inclement weather they act as a guide for the travel lanes. Truck drivers have stated that the continuous shoulder rumble strips serve as an aid in determining the edge of the traveled way in low visibility conditions, such as heavy snow,

fog, and ice. Additionally, in mountainous terrain they have provided tread for vehicles traveling up large slopes. (Chen, 1994; Elefteriadiou, 2000).

3. On high speed, limited access highways, given the high speeds and higher design levels, the chances for high speed run off road crashes are at their highest. In any event, it is undesirable for bicyclists to cross the SRS in these situations for any reason. Further, given driver expectations on these facilities, it is highly desirable for bicyclists, who must cross, to walk (run) their bicycles rather than ride them when crossing the facility.
4. According to a FHWA study (2000), most states use continuous SRS and mostly on the Interstate system. In short, these high type facilities are in the most need of the most effective SRS design, which is the continuous design, bicyclists should be discouraged from crossing these facilities, most states use continuous designs, and FHWA recommends their use as well.
5. On other roadways, on the other hand, if cyclists need to traverse a rumble strip, they should be able to do so without incident, though it is generally accepted that the experience is annoying (Garder 1995). Of course, continuous design does not allow cyclists to cross the SRS without riding over the strip, thus the need for intermittent design on these types of facilities. Intermittent design provides regular opportunities for cyclists to cross the SRS without crossing over the portions of the strip that they find objectionable and in some cases unsafe. Moeur (2000) experimented with placing intermittent gaps between sections of rumble strips and studied how well bicyclists of various skill levels and on different bicycle types could maneuver using a test speed of 25 mph. Based on these data he recommended that SRS on all non controlled access highways include periodic gaps of 12 feet in length and these gaps be placed at periodic intervals at recommended spacing of 40 feet or 60 feet (for ease of construction). Assuming a 3- degree departure angle and factoring in an 8 inch tire width, Moeur found that it would be virtually impossible for the tire to completely miss a set of rumble strips that included 12-foot gaps, even in a rumble strip as narrow as 5 inches. He recommends that the same gap length and cycle should be used for all widths of rumble strips. Indeed, for a 12" wide SRS, a vehicle departure angle of at least 8 degrees would be required to "miss" the SRS whereas the vast majority of lane departures are in the 3 degree to 5 degree range.
6. Where appreciable bicycle traffic exists or is anticipated on non-access-controlled highways with shoulders less than eight (8) feet, Arizona provides a 10-foot gap for bicyclists to traverse the rumble strip treatment. For such situations, the rumble strip pattern consists of 30-foot long segments of rumble strips, with 10-foot segments of no rumble strips, on a 40-foot cycle. Outcalt (2001) found that the 12 foot gap with 60 foot period, milled-in, provided the best vibration stimulus of any alternatives considered and is the design proposed for Missouri.
7. Both the League of American Bicyclists (LAB August 2001) and the Minnesota Coalition of Bicyclists [MCB, n.d.] support the use of intermittent SRS.

4.7 Offset from shy line

The closer that rumble strips are installed to the shy line, the sooner the motorist receives an auditory and vibrational warning. Location of rumble strip installation is critical to its effectiveness. For every foot the rumble strip is offset from the edge of the travel lane, there is an additional 0.03-second delay in warning. Additionally, with minimum offset, bicyclists are provided the maximum clear zone. Conversely, this may also cause increases in ambient noise due to inadvertent encroachment onto the SRS. For these reasons, and given that the SRS are primarily used in rural, low development areas, it is recommended that the offset used on non-controlled access highways be zero. With the increased shoulder widths on freeways, the criticality of bicyclist clear zones and room for recovery reduces, thus it is recommended that the offset on these facilities be 6 inches on both right and median shoulders.

Harwood (1993) found that continuous rumble strips (which are the type proposed for installation on freeway sections) that are placed too close to the travel lane have caused snowplowing problems on the travel lane.

From the standpoint of the motorist, placement of the SRS adjacent to the roadway is desirable in that it gives early warning of having left the traveled way and provides maximum recovery distance.

It also avoids the snow plowing issue and stays within the two foot area that lies between painted edge line and shoulder joint on concrete pavement sections. From the standpoint of the bicyclist, placement of the SRS as close to the edgeline of the roadway as possible allows the cyclist to have a buffer between themselves and the motor vehicle traffic, yet allows space for them in the portion of shoulder generally clear of debris. Most States are following the practice of installing the SRS near the edge line (Nedzesky, 2001). Indeed, Cheng found (2000) that most cyclists prefer that SRS be placed near the shy line.

5.0 CONCLUSIONS

This multi-phase project examined the use and design of SRS in the State of Missouri. In addition to a set of guidelines that are provided in the Recommendations section of this report, two specific research questions were posed at the outset of the work, namely, can SRS be narrowed from the current 36" width and be moved closer to the edge line to encourage bicyclists to ride on the right side of the strip further from traffic, and, for concrete pavements, can strips be narrow enough to avoid the construction joint with the shoulder. The answers to both of these questions are yes. As described in the next section, SRS width and offset required for motorist safety are well within the bounds of these two questions.

6.0 RECOMMENDATIONS

The following recommendations are offered in three parts: a list of warrants for placement of SRS, policy and guidelines for placement and design, and an evaluation framework for assessing SRS designs.

6.1 Warrants

1. Facility Type. Install on all rural freeways and expressways.
2. Urban versus Rural. Do not install in urban areas unless an engineering study has been conducted and has found that run off road crash history exceeds acceptable values (Ohio, for example, uses 25 crashes per hundred million vehicle miles) and it is determined that SRS would be effective in reducing those numbers.
3. Speed limit. Speed limit must exceed 45 mph
4. Free Shoulder Width. On non-freeway/expressway sections, free shoulder width (that available for cyclists) must exceed four feet (five feet in guard rail sections). Shoulders not meeting these criteria are not wide enough to accommodate both SRS and cyclists. In this latter event, decision must be made whether, for shoulders wider than two feet, whether crash history (Ohio for example as above) or cyclist usage (for example, one state uses volumes exceeding 25 ADT for the peak three months of the year) should be given priority on the facility. When SRS are installed in this case, cyclists must be denied access to the facility. For shoulders less than two feet wide, SRS should not be installed.
5. Uninterrupted Length. The uninterrupted length of highway must exceed 1/30 of the design speed.

6.2 Proposed Shoulder Rumble Strip Policy

6.2.1 Introduction

The purpose of this policy is to define when and where shoulder rumble strips (SRS) may be applied on the state highway system. It will, upon approval, replace the current MoDOT policy shown below:

6-04.6 RUMBLE STRIPS. *Rumble strips are to be included on all routes where the shoulder is concrete or the final lift of bituminous material is at least 1-³/₄ in. [45 mm] thick, the shoulder has a final paving thickness of at least 3-³/₄ in. [95 mm] and the shoulder has a minimum width of 3 ft. [0.9 m], unless the shoulder has a curbed section or the shoulder is intended to be used as a future travel lane. Rumble strips are to be rolled into the hot*

bituminous material or formed in the plastic concrete of shoulders on new and resurfaced projects. See Standard Plan 626.00. Rumble strips are to be omitted adjacent to ramps, acceleration and deceleration lanes including tapers and between the radius points for side road approaches, entrances and median crossovers.

Highway shoulder rumble strips are intended to enhance safety by preventing run-off-road crashes. They accomplish this by alerting drivers of errant vehicles by providing audible and tactile warning. Studies have shown that shoulder rumble strips provide significant decreases in run-off-road crash rates.

6.2.2 Policy

Shoulder rumble strips (SRS) shall be placed on all highway projects that meet the warrants shown in Figure 6.1. Districts should also consider placing SRS on existing shoulders at locations with a high run-off-road crash rate, that meet the warrants in Figure 6.1 and on which no reconstruction is scheduled in the near future. The District Operations Engineer should make recommendations regarding structural adequacy of existing shoulders for this purpose. Types and applications of SRS are shown in Table 6.1. Figures 6.2 and 6.3 provide section and plan views of SRS.

Notes on SRS placement and design

1. All SRS shall be milled and 7/16" ± 1/16" deep. For new concrete pavement construction, the contractor may choose to use formed SRS rather than milled.
2. SRS pattern shall be 5" ± 1/2" grooves, 12" OC
3. Do not install in driveways, intersections, suburbs or residential areas
4. Do not use if shoulder is being considered for peak flow lane
5. Consider widening shoulders that are less than 8' in width in areas with SRS installed, significant bicycle traffic and extended steep downhill grades.
6. Given that the SRS are primarily used in rural, low development areas, it is recommended that the offset used on non-controlled access highways be zero
7. With the increased shoulder widths on freeways, the criticality of bicyclist clear zones and room for recovery reduces, thus it is recommended that the offset on these facilities be 6 inches on both right and median shoulders

Table 6.1 SRS Design Dimensions

Application	Rumble Strip Type
Freeway shoulders	16" wide, 6" offset, continuous
<i>Non freeway shoulders</i>	
Shoulder width ≥ 6 ft.	16" wide, 6" offset, intermittent - 12 foot gaps, 60 foot cycles
Shoulder width 5 ft. to 6 ft.	12" wide, 0" offset, intermittent - 12 foot gaps, 60 foot cycles
Shoulder width 2 ft. to 5 ft.	May be wide enough for SRS or bicyclists: Conduct needs studies for SRS and bicycle use
Shoulder width < 2 ft.	Too narrow for either SRS or bicyclists

6.3 Evaluation of SRS

Evaluation of SRS requires that their objectives be explicitly identified and that measures be established for use in the evaluation process. Run-off-the-road crashes represent a significant

percentage of fatal and injury crashes in Missouri as discussed earlier in this report. Shoulder rumble strips have proven to be an effective roadside treatment in preventing run-off-the-road crashes on rural highways. They also create problems for the biking community and for abutters to facilities on which they are installed. Their objective, then, is to reduce ROR crashes while addressing the needs of bicyclist and of adjacent communities . The following objectives are proposed for use in evaluating Missouri’s SRS policy:

1. Benefit-cost analysis of SRS system
2. Surveys of constituencies

6.3.1 Benefit-Cost Ratios

The following information is provided solely to be used as a guide in evaluating SRS in Missouri. Suggestions as to how and where costs and benefits may be obtained are provided. Typical values are also provided.

The cost of shoulder rumble strips-milled may be obtained from the MODOT Weighted Average Bid Prices. Wyoming’s costs are \$0.194 per linear foot based upon a contract quantity of 2.95 million linear feet. Virginia’s recently received a contract unit price of \$0.125 per linear foot on an overall quantity of 2.5 million linear feet. These unit prices are taken from the full contract bid and include other items such as mobilization and traffic control. For the 2,828 miles of rural primary arterials (including expressways, freeways, multi-lane roads, one way roads, and super 2-lane highways) in Missouri, and assuming about 2 times that number of miles for SRS installation, this translates to a cost of \$3,733,027.

Benefits of SRS derive from reductions in ROR crashes. Numerous studies have been completed to determine the effectiveness of shoulder rumble strips in reducing single vehicle run-off-the-road crashes and are summarized in Table 6.2.

Table 6.2 Summary of SRS Crash Reductions

State/Date	Highway Type	% Crash Reduction
Pennsylvania/1994	Thruway - Rural	70
New Jersey/1995	Turnpike - Rural	34
New York/1994	Thruway - Rural	72
Massachusetts/1997	Turnpike - Rural	42
Washington/1991	Six Locations	18
California/1985	Interstate - Rural	49
Kansas/1991	Turnpike - Rural	34
FHWA/1985	Interstate - Rural (Five States)	20

The FHWA study included rural Interstate locations in California, Arizona, Mississippi, Nevada, and North Carolina. The California locations were the same as used in the California study and if the California locations are omitted, the remaining four States showed a 6 percent reduction.

These studies produce a wide variation in the percent crash reduction attributable to shoulder rumble strips. Harwood (1993) concludes that a 20 percent system-wide reduction in run-of-the-road crashes can be expected with the incorporation of shoulder rumble strips, with reduction rates up to 70 percent reserved to isolated, long, monotonous stretches of rural highways. A reduction rate for the State of Missouri should be a continually changing value based upon the run-off-road crash experience on sections of road on which rumble strips are installed.

Values for fatal, injury and property damage only crashes may be taken from the Missouri Manual on High Accident Locations (MODOT, 1999). The values are:

- Fatalities \$3.390,000
- Injuries \$44,100
- PDO \$ 3,220

Thus, for example, using MODOT's crash summaries, 74 fatalities, 1,454 injuries and 2,194 PDOs occurred in the year 2001. Applying the equation shown below, the total cost of these crashes is \$330,076,240.

Total costs= (% Fatal * \$3,390,000 + % Injuries * \$44,100) * (74 + 1454) + 2194 * \$3,220

where % Fatal = 5%, % Injury = 95% (of total fatal and injury accidents)

If these were to reduce, across the board, by 20%, the resulting benefit would be approximately \$66,015,248. It should be noted that all crashes shown occurred on sections of road of the type named above and it is assumed that all occurred on sections of road without shoulder rumble strips installed. In actual practice, ROR crash reductions occurring on newly installed rumble strips would need to be collected. For example, data for year 1 would include only road segments that have no rumble strip but for which rumble strip construction was to be done during the coming year. Data for year 2 would include those same road segments. In this way, a crash reduction could be calculated by crash category and could then be used to calculate an estimated benefit.

Using the numbers from this example the B/C ratio is 17.7.

6.3.2 Surveys of Constituencies

This may be done in any number of ways. Two are suggested here as illustrative of the types of information that may be collected. The first is to use MODOT's Bike Coordinator to disseminate current MoDOT policy on SRS and to conduct a survey once a year at the Bike Federation annual meeting. This would provide valuable information regarding how well the biking constituency is being served. The second constituency of interest is the abbuttors to SRS facilities. Their input could be elicited via MoDOT's website, perhaps along with some limited direct mailings.

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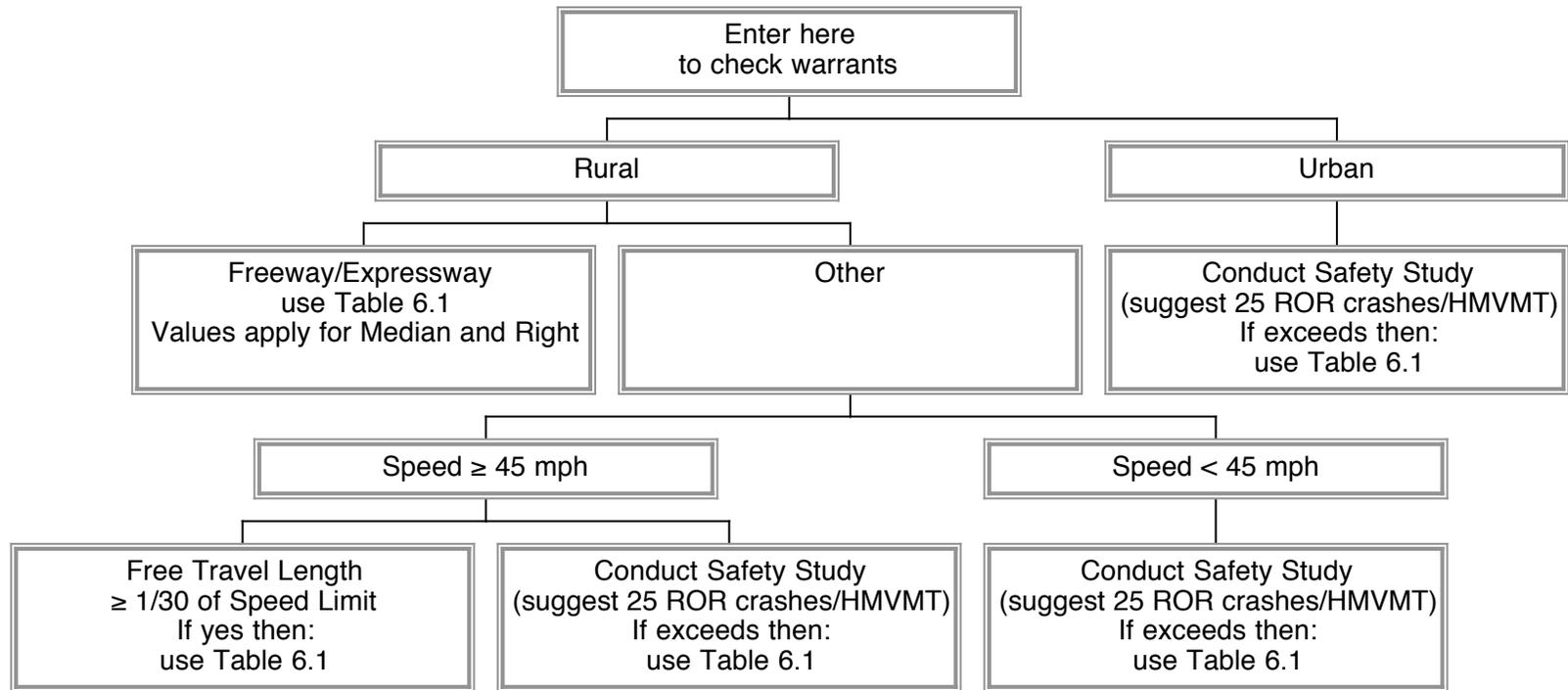
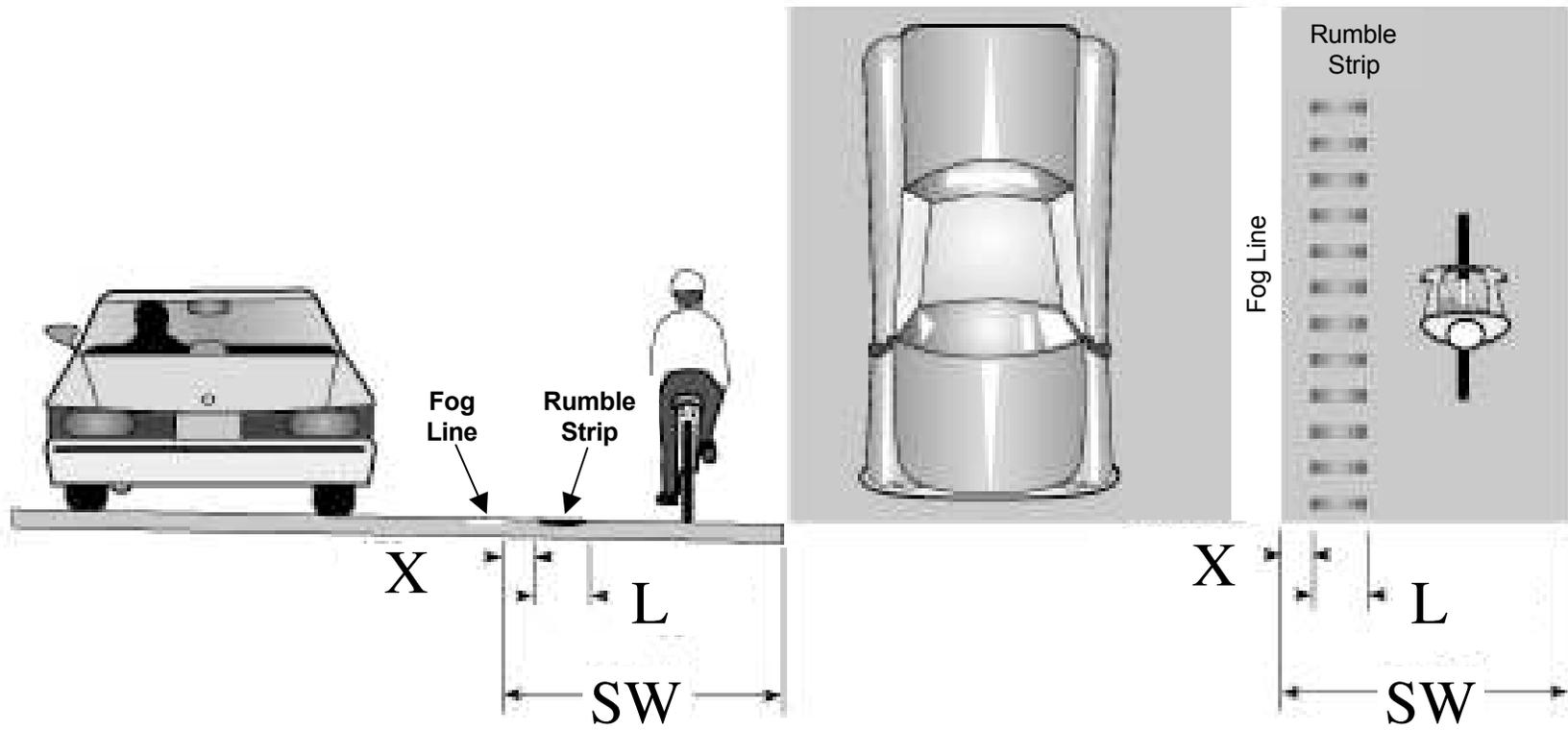


Figure 6.1 Warrants for SRS



Dimensions
 X, offset, varies 0" or 6"
 L, length, varies 12" or 16"
 SW, shoulder width varies - minimum is 4 feet.

Figure 6.2 SRS Design Dimensions

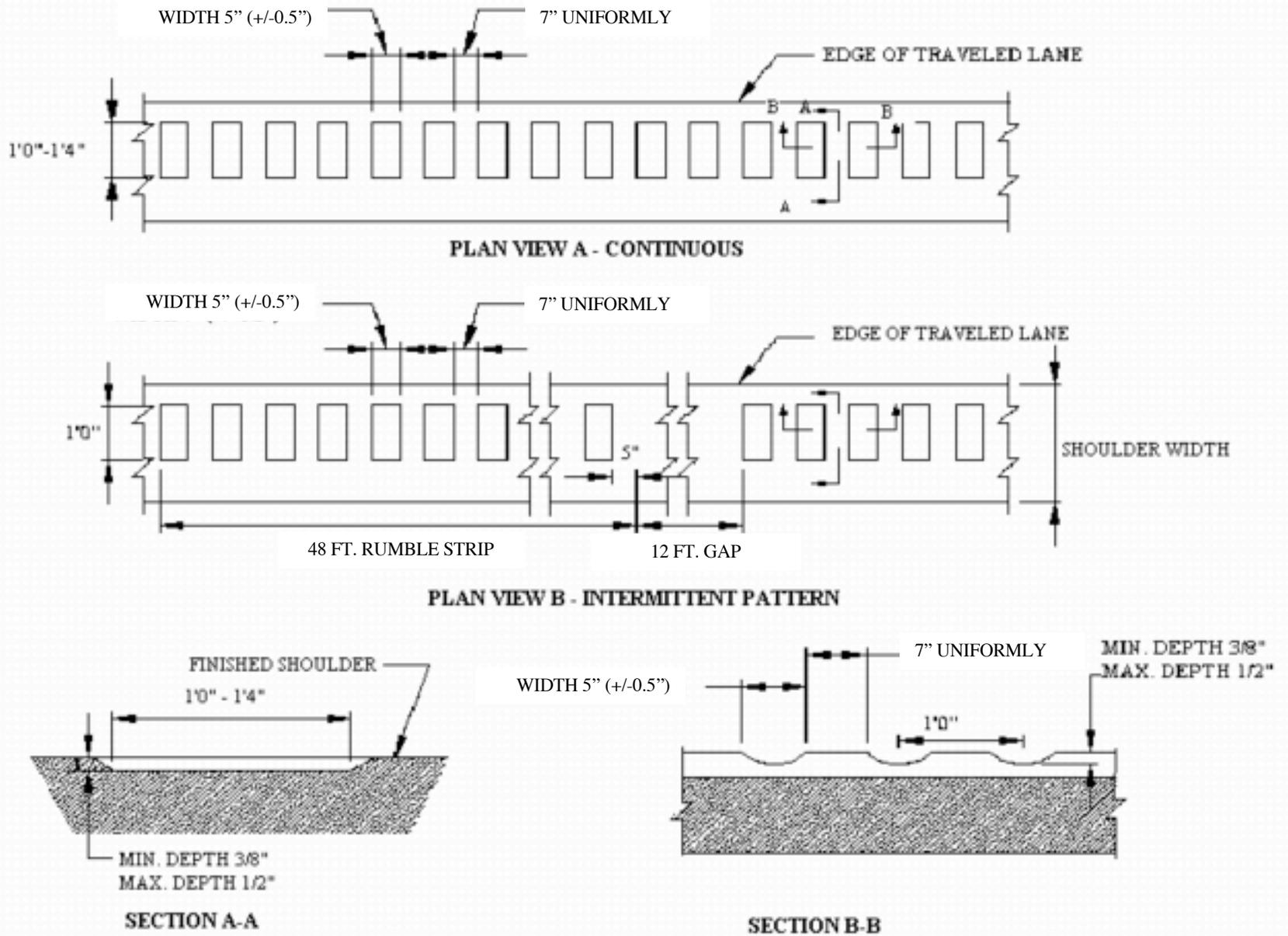


Figure 6.3 SRS Design Details

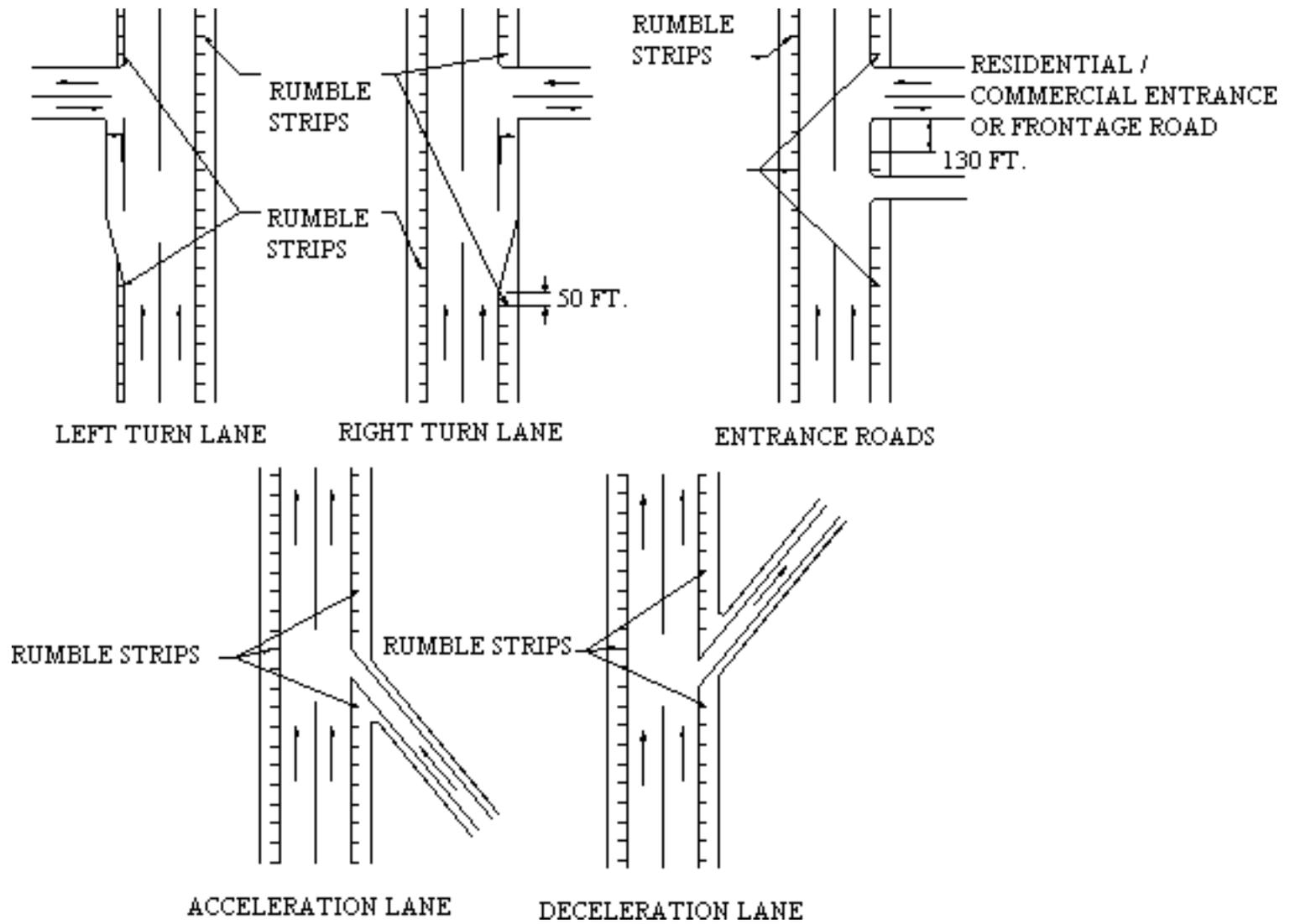


Figure 6.4 SRS Layout Details